International Space Station Bus Regulation With NASA Glenn Research Center Flywheel Energy Storage System Development Unit

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ABSTRACT
An experimental flywheel energy storage system is described. This system is being used to develop a flywheel based replacement for the batteries on the International Space Station (ISS). Motor control algorithms which allow the flywheel to interface with a simplified model of the ISS power bus, and function similarly to the existing ISS battery system, are described. Results of controller experimental verification on a 300 W·hr flywheel are presented. Keywords: flywheel, motor control, battery, charge, discharge, charge reduction.

INTRODUCTION
A developmental flywheel test facility has been built at NASA Glenn Research Center (GRC), in Cleveland, Ohio. This system includes a carbon composite high-speed flywheel, which is coupled to a motor/generator, and is suspended by active magnetic bearings. This test facility allows development and testing of control algorithms for the flywheel motor/generator and magnetic bearings. Flywheel based energy storage systems are being considered as a possible replacement for the battery based system currently in use on the ISS because flywheel systems feature longer life, higher efficiency and greater depth of discharge than battery based systems. In order to allow direct replacement, the flywheel system must be made to operate in the same fashion as the battery systems currently in place on the ISS. This paper describes motor/generator control algorithms which allow the flywheel system to interface with a simplified version of the ISS electrical bus, enabling the flywheel to be "charged" by storing energy mechanically in the wheel, and "discharged" by converting mechanical energy to current on the bus, while regulating bus voltage.

NOMENCLATURE

\* - charge current setpoint
\* - DC current regulator setpoint
\_d - d-axis current in the rotor reference frame
\_q - q-axis current in the rotor reference frame
\CRCD - current set point for charge reduction/discharge modes
\flywheel - DC Current into the Flywheel
\load - load current
\array - solar array current
ISS - International Space Station
BCDU/BS - Battery Charge Discharge Unit/Battery System
\_d - d-axis stator inductance, H
\p - time derivative operator (d/dt)
P - number of poles
\flywheel - Power on the AC side of the inverter
\_R - Stator resistance per phase, Ω
SAS - Solar Array System
SAW - Solar Array Wings
SSU - Sequential Shunt Unit
\dc - DC bus Voltage
\array - d-axis voltage in the rotor reference frame
\array - q-axis voltage in the rotor reference frame
\S - Sequential Shunt Unit voltage set point
\discharge - flywheel (or BCDU) discharge voltage set point

\* - flux due to the rotor magnets
ISS POWER BUS CONFIGURATION

Power for the ISS is generated by the station solar array system (SAS), which includes the solar array wings (SAW) and the sequential shunt unit (SSU). Since the SAS cannot generate energy within the 35 minute eclipse period of the 92 minute ISS Earth orbit, some energy needs to be stored aboard the ISS. Presently, this energy is stored and regulated in a battery-based system called a Battery Charge Discharge Unit/Battery System (BCDU/BS). In order for a flywheel system to replace the BCDU/BS on the ISS, it must mimic the electrical performance of the BCDU/BS. In the following text, present BCDU/BS operation is described, and required flywheel operation is noted in parentheses. Figure 1 is a schematic of the present BCDU/BS (proposed flywheel) system.

![Solar Array System Diagram](image)

**Figure 1: Block Diagram of ISS BCDU/BS (Flywheel) Power System**

The BCDU/BS (flywheel) has three operational modes - the "charge" mode, the "discharge" mode, and the "charge reduction" mode. These modes of operation are summarized in Table 1.

<table>
<thead>
<tr>
<th>Mode</th>
<th>BCDU/BS (Flywheel) DC Current</th>
<th>Regulated Bus Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge</td>
<td>( I_{BCDU/BS} = I_{charge} )((I_{flywheel} = I_{charge}))</td>
<td>( V_{bus} = V_{s/a} )</td>
</tr>
<tr>
<td>Discharge</td>
<td>( I_{BCDU/BS} &lt; 0 ) ((I_{flywheel} &lt; 0))</td>
<td>( V_{bus} = V_{charge} )</td>
</tr>
<tr>
<td>Charge Reduction</td>
<td>( I_{charge} &gt; I_{BCDU/BS} &gt; 0 ) ((I_{charge} &gt; I_{flywheel} &gt; 0))</td>
<td>( V_{bus} = V_{discharge} )</td>
</tr>
</tbody>
</table>

**Table 1: BCDU/BS (Flywheel) Modes of Operation**

Discharge mode on the energy storage system occurs when the batteries are discharging (flywheel is decelerating) and providing power to the load. In this mode, the BCDU (flywheel) regulates the DC bus voltage at \( V_{discharge} \). This discharge mode typically takes place when the station is in full eclipse.

Charge reduction mode on the energy storage system occurs when the SAS provides some current, but not enough to both supply the load and charge the batteries (accelerate the flywheel) at the charge mode current setpoint. In this mode, the BCDU (flywheel) provides regulation of the DC bus at \( V_{discharge} \). This charge reduction mode typically takes place when the station is in partial sun.

FLYWHEEL TEST CONFIGURATION

A simplified schematic of the flywheel test configuration is presented in Figure 2. In this system, the ISS bus is modeled using a commercially available DC power supply as the source, and a resistor as the load. For charge mode operations, the supply was set to 60V and 30A current limit; for discharge mode, the current limit of the supply was brought down to 0A. The load resistance value was changed to simulate different loading conditions during discharge mode. Although the flywheel is rated at 60,000 RPM, speed was limited to under 10,000 RPM during controller testing. The input filter to the inverter was a 13.2 mF capacitor.

![Flywheel System Diagram](image)

**Figure 2: Simplified Flywheel Test Configuration**

The entire motor/generator portion of the flywheel development system is shown schematically in Figure 3; this system includes the hardware presented in Figure 2, along with details of the motor control system and the DC bus controls. A commercially available computer was used for the controller (DC bus control system design and operation is described in detail in the following sections). The motor control signals are converted via a PWM board, and passed on to a commercially available inverter, which drives the flywheel motor. Inverter power was supplied by the simplified ISS bus (see Figure 2). Feedback signals for the controller include two motor phase currents \( (I_a \text{ and } I_b) \), the motor once around (OAR) signal, and the DC bus current and voltage \( (d_c \text{ and } V_d) \).
DC BUS CONTROL OVERVIEW

The DC bus controller must control the flywheel motor such that the dc bus current, \( I_{flywheel} \), (in charge mode) and the dc bus voltage, \( V_{dc} \), (in discharge mode) are regulated. This is done in the block labeled "Charge/Discharge Current/Voltage Regulator" (CDCVR) in Figure 3. The input variables to this block are the commanded and measured values of the dc bus voltage and current. The output variable is the current command to the inner loop motor control algorithm (\( i_{qs} \)). This motor control algorithm is based on the field orientation technique that is described in [1].

The CDCVR block for the DC bus control consists of three main functions:

1. Regulate the dc charge current to the flywheel system, \( I_{flywheel} \), to the commanded value, \( I_{charge}^* \), set by a higher-level ISS control during charge mode.
2. Regulate the station DC bus voltage, \( V_{dc} \), to commanded value, \( V_{dc}^{charge} \), set by the higher-level ISS control during charge reduction and discharge modes.
3. Transition smoothly between charge, charge reduction and discharge modes.

Two types of CDCVR controls were investigated: proportional-integral (PI) control, and PI plus feedforward control.

CDCVR PROPORTIONAL INTEGRAL (PI) CONTROL

The PI version of the CDCVR control configuration is shown in Figure 4. This PI control configuration consists of two control loops, the DC voltage loop (for discharge mode and charge reduction mode) and the DC current loop (for charge mode), and also two transition conditions.

When the flywheel system is in charge mode, the \( I_{flywheel}^* \) switch is in position 1 making it equal to \( I_{charge}^* \). At this stage, the output of the PI regulator sets the inner loop motor current command, \( i_{qs}^* \), based on the error between the commanded flywheel current (\( I_{flywheel}^* \)) and the measured flywheel current (\( I_{flywheel} \)). In the charge mode, \( I_{flywheel} \) is positive and the solar array system (SAS) regulates the dc bus voltage.

![Figure 4: PI CDCVR Control Algorithm](image-url)
current. Once $I_{\text{flywheel}}$ reaches the charge current set point, $I_{\text{charge}}$, it is an indication that the solar array is now producing enough current to provide all of the station loads plus $I_{\text{charge}}$. At this point, the flywheel system must transition from voltage regulation to current regulation and the solar array system will begin to regulate the dc bus voltage.

Current and voltage regulation are detected in the PI CDCVR Control in the following way and will be described using an example. Starting in charge mode, the dc bus voltage, $V_{\text{dc}}$, is at 130 volts, controlled by the solar array. The flywheel voltage set point, $V_{\text{flywheel}}$, is at 120 volts. The voltage transition constant (VTC) is -5 volts (see Figure 4). Thus in charge mode, $V_{\text{flywheel}} - V_{\text{dc}}$ is less than the VTC (-10 < -5) and the integrator is not reset. These conditions produce a $I_{\text{CRD}}$ value larger than $I_{\text{charge}}$, which causes the $I_{\text{flywheel}}$ switch to move to position 1 (charge mode).

As the solar arrays move into eclipse, the dc bus voltage falls. As the bus voltage falls below 125 volts, $V_{\text{flywheel}} - V_{\text{dc}}$ falls below the VTC, and the integrator resets to 0. This sets $I_{\text{CRD}}$ to a small positive number. Since $I_{\text{CRD}}$ is now less than $I_{\text{charge}}$, the $I_{\text{flywheel}}$ switch is moved to position 2 and the system transitions into voltage regulation (charge reduction/discharge mode).

As long as the flywheel current, $I_{\text{flywheel}}$, is less than the charge set point current, $I_{\text{charge}}$, the system remains in voltage regulation because the solar arrays are not providing enough current to meet the load demands and the current charge set point. As the station moves out of eclipse, the SAS begins to contribute current, increasing the bus voltage ($V_{\text{dc}}$) until $V_{\text{flywheel}} - V_{\text{dc}}$ drops below VTC. At this point, voltage PI loop integrator will no longer be reset, $I_{\text{CRD}}$ will exceed $I_{\text{charge}}$, and the $I_{\text{flywheel}}$ switch will move to position 1, transitioning the system to current regulation (charge mode).

**CDCVR PI PLUS FEEDFORWARD CONTROL**

The PI control described in the previous section and in Figure 4 is structured such that the inner loop motor command current, $i_{qs}$, is derived from a PI controller operating on a $I_{\text{flywheel}}$ command. In charge mode, $I_{\text{flywheel}}$ is equal to the charge current set point, $I_{\text{charge}}$. In discharge mode, $I_{\text{flywheel}}$ is equal to $I_{\text{CRD}}$, the charge reduction/discharge current set point. In either case, $i_{qs}$ is the output of a PI control operating on the error between $I_{\text{flywheel}}$ and $I_{\text{flywheel}}$.

There is another approach to producing the motor current command based on the desired $I_{\text{flywheel}}$ value that is shown in Figure 5. In this approach, the open loop steady state relationship between $i_{qs}$ and $I_{\text{flywheel}}$ is used to determine $i_{qs}$ from $I_{\text{flywheel}}$. This approach allows the use of a feedforward command for both voltage and current regulation, which results in a fast response with lower gains on the PIs. The lower PI gains result in less noise in the system as will be shown in the experimental results section.
\[ V_{DC} I_{DC} = \frac{3}{2} (\omega_r \lambda_{af} i_{gq}^*) \]  

This can be used to relate a current command on the dc side of the inverter to a current command on the ac side of the inverter:

\[ i_{gq}^* = \frac{2V_{DC} I_{DC}}{3\omega_r \lambda_{af}} \]  

From (9) it can be seen that during current regulation (charge mode) the feedforward command to the motor current is

\[ i_{gq}^* = \frac{2V_{DC} I_{change}}{3\omega_r \lambda_{af}} \]  

Figure 5 shows that the charge current set point, \( I_{charge} \), sums with the output of the PI regulator that operates on the error between \( I_{charge} \) and \( I_{flywheel} \). Under current regulation (charge mode), \( I_{flywheel} \) is equal to this sum. If the feedforward relationship of (10) is exactly accurate, then the contribution of the PI portion to \( I_{flywheel} \) will be zero. However, approximations were made in the derivation of (10) plus the back emf constant, \( \lambda_{af} \), may not be known exactly. So the PI is used to make up for any errors in the feedforward calculation. However, the feedforward portion is contributing most of the \( I_{flywheel} \) command so the gains on the PI can be set lower than in the previous case (PI only algorithm).

Similarly for voltage regulation (discharge and charge reduction modes) the feedforward command to the motor current is

\[ i_{gq}^* = \frac{2V_{flywheel} I_{flywheel}}{3\omega_r \lambda_{af}} \]  

Figure 5 also shows that \( I_{flywheel} \) sums with the output of the PI regulator that process the error between \( V_{flywheel} \) and \( V_{dc} \). Under voltage regulation (discharge and charge reduction modes), \( I_{flywheel} \) is equal to this sum. Similar to the current regulation (charge mode) control loop, the feedforward portion of the voltage regulation loop is contributing most of the \( I_{flywheel} \) command so the PI gains can be set lower than in the PI only algorithm.

Furthermore, Figure 5 shows the \( I_{flywheel} \) command converted to the \( i_{gq}^* \) command through the power balance relationship of (9). For current regulation, \( V \) in this block is equal to the measured value \( V_{dc} \). For voltage regulation, \( V \) in this block is equal to the commanded value, \( V_{flywheel} \). In both cases, the speed, \( \omega_r \), is measured and used as an input to this block.

The transition characteristics between current regulation and voltage regulation for this PI plus feedforward control are the same as described in the previous section for the PI only control.

**EXPERIMENTAL RESULTS**

To verify the proper operation of the two described control loops and prove that the flywheel system can perform like a BCDU/BS, two types of tests were performed. The first test was a step change on the charge set point and the second test was a load step while the flywheel was in discharge mode. These tests were performed on both the PI and the PI plus feedforward controllers.

The two controllers were tuned to have similar responses. This was achieved by using approximately 1 order of magnitude higher gains for the PI only control than the PI plus feedforward control. There was very little difference between the PI only and the PI with feedforward performance in the response of the DC bus variables, \( I_{flywheel} \) and \( V_{dc} \). Thus for the DC bus variables, only the results for the PI plus feedforward control are presented.

Figure 6 shows the response to a step change in commanded current during charge mode. The transient response time was about 12 msec. As mentioned previously, the combination of the SAW and SSU is experimentally modeled using a DC power supply. Because the measurement of DC current is taken on the power supply side of the capacitor, most of the current transient is caused by the reaction of the power supply to the change in current taken by the flywheel system.

![Figure 6: \( I_{flywheel} \) Response for Charge Mode Current Step Change Using PI Plus Feedforward Control Algorithm](image-url)

Figure 7 shows the system operating in discharge mode (flywheel system regulating the dc bus voltage) with a step change in load. Discharge mode is experimentally modeled with the power supply turned off, therefore the step response is entirely due to the flywheel system. The discharge voltage set point, \( V_{flywheel}^* \), is set to 60 volts. Figure 7 clearly shows that the bus voltage regulation is maintained for this load step.

Figure 8 shows the flywheel speed for the same load step shown in Figure 7. It can be seen that when the load is applied the slope of the speed trace becomes more negative. This is because more power is taken from the flywheel system and delivered to the load.
Figures 9 and 10 show the flywheel system motor phase current response for the same load step shown in Figure 7 for pure PI and PI plus feed forward controllers respectively. It is clear that the phase currents for the pure PI controller are much noisier than with the PI plus feedforward controller. This is because the correcting PI loop on the PI plus feedforward controller can have very small gains due to the action of the feedforward portion of the control. The pure PI controller requires larger gains to achieve similar performance; these large gains increase the control bandwidth, allowing the controller to act on noisy feedback signals (i.e. the DC bus voltage).

CONCLUSIONS
DC bus regulation during changes in charge current set point and discharge load value was demonstrated on the flywheel development unit. Additionally, CDCVR regulator mode transition algorithms were implemented and discussed. These results demonstrate that a flywheel system can successfully mimic the operating modes of the ISS battery system. This is an important milestone because it is a first step in demonstrating the feasibility of replacing the ISS battery system with a flywheel system.

REFERENCES
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